

PB86-126711

Length Scale of Turbulence above
Rough Surfaces

(U.S.) Environmental Protection Agency
Research Triangle Park, NC

Nov 85



U.S. Department of Commerce
National Technical Information Service
NTIS

EPA/600/D-85/286
November 1985

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TECHNICAL REPORT DATA <i>(Please read Instructions on the reverse before completing)</i>		
1. REPORT NO. EPA/600/D-85/286	2.	3. RECIPIENT'S ACCESSION NO. PB8 6 1267117AS
4. TITLE AND SUBTITLE THE LENGTH SCALE OF TURBULENCE ABOVE ROUGH SURFACES	5. REPORT DATE November 1985	
	6. PERFORMING ORGANIZATION CODE	
7. AUTHOR(S) Clarke, J.F., Binkowski, F.S., Ching, J.K.S., Godowitch, J.M.	8. PERFORMING ORGANIZATION REPORT NO.	
9. PERFORMING ORGANIZATION NAME AND ADDRESS Atmospheric Sciences Research Laboratory Office of Research and Development U.S. Environmental Protection Agency Research Triangle Park, NC 27711	10. PROGRAM ELEMENT NO. CDWA1A/02-1324 (FY-86)	
	11. CONTRACT/GRANT NO.	
12. SPONSORING AGENCY NAME AND ADDRESS Atmospheric Sciences Research Laboratory - RTP, NC Office of Research and Development U.S. Environmental Protection Agency Research Triangle Park, NC 27711	13. TYPE OF REPORT AND PERIOD COVERED	
	14. SPONSORING AGENCY CODE EPA/600/09	
15. SUPPLEMENTARY NOTES		
16. ABSTRACT Results of analyses of data for two urban sites and a rural site suggest that the mixing length can be represented by the integral length scale of the turbulence derived from vertical velocity spectra. The result is apparently universal and permits the shear production of turbulent kinetic energy to be estimated by measurements at a single level within the surface boundary layer.		
17. KEY WORDS AND DOCUMENT ANALYSIS		
a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COBATI Field/Group
18. DISTRIBUTION STATEMENT RELEASE TO PUBLIC	19. SECURITY CLASS (This Report) UNCLASSIFIED	21. NO. OF PAGES 7
	20. SECURITY CLASS (This page) UNCLASSIFIED	22. PRICE

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THE LENGTH SCALE OF TURBULENCE ABOVE ROUGH SURFACES

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1. INTRODUCTION

A major urban surface boundary layer turbulence measurement study was conducted in St. Louis, Missouri, in 1976 as part of the Regional Air Pollution Study (RAPs) (Schiermeier, 1978). The data consisted of Gill type UVW propeller anemometer and fast response temperature measurements recorded at a 0.5s interval from the top of 30-m towers at two urban sites (sites 105 and 107) and a rural site (site 109) in the St. Louis metropolitan area. Data were recorded continuously (except for calibration and repairs) over a five week period in July-August and during a four week period in October-November 1976. The field program and analysis of these data have been reported in Clarke et al. (1982).

The analysis program was directed to testing the applicability for urban areas of turbulence parameterizations derived from experiments at ideal sites (e.g., the Kansas and Minnesota studies). The report of this study (Clarke et al. 1982) concluded that the statistics of turbulence at an urban site are different from those over ideal terrain. The differences are attributed to the influence of a combination of factors, including: 1) building wake effects arising from the relative nearness of the measurements above the roughness elements, 2) abrupt changes in upwind roughness that introduce advective and nonsteady effects, and 3) urban heat island scale influences in which vertical advection and flux divergence processes are important.

A limitation of the study was that profile measurements were not obtained and consequently we were limited in the types of analysis that could be accomplished. In an effort to overcome this limitation we made extensive analyses of the spectra under the contention that the major features of the turbulence structure are described by the spectra. The analysis of the spectra led us to the conclusion that the integral length scale of the vertical velocity fluctuations, L_{iw} , is a very good approximation of the mixing length and can be used to define the shear production term in the turbulence kinetic energy (TKE) budget equation.

* On assignment from the National Oceanic and Atmospheric Administration, U.S. Department of Commerce.

2. MIXING LENGTH APPROXIMATION

The shear production of TKE is usually expressed as $u^*^2 du/dz$ (u^* is the surface stress and du/dz is the vertical wind shear). From the definition of mixing length, $\lambda = u^*/du/dz$, the shear production term can be expressed as u^*^3/λ . This expression is expected to be universally valid regardless of surface conditions or stratification. There exists no direct expression for λ . However, any such expression should be consistent with the empirical form of the nondimensionalized wind profile (for homogeneous surfaces) suggested by Businger et al. (1971), given by:

$$\phi_m = kzdu/dzu^* = kz/\lambda \quad (1)$$

For neutral stratification $\phi_m = 1$ and it follows that $\lambda = kz$. For unstable stratification $\phi_m = (1 - 15z/L)^{-1/4}$ (Businger et al., 1971) resulting in $kz/\lambda = 0.42$ and 0.34 for $z/L = -2$ and -5 , respectively. Thus for unstable stratification λ is approximately given by the height above the surface, z . We would further expect λ to be related to the spectral length scales and suggest:

$$\lambda = AL_{iw} \quad (2)$$

where A is a constant to be determined.

The experimental data of Teunissen (1971) suggest that for neutral stratification $L_{iw} = kz$ and consequently $L_{iw} = \lambda$ and $A = 1.0$. For unstable stratification, L_{iw} , like λ , is roughly given by z within the uncertainty of the observations of z/L_{mw} (L_{mw} is peak wavelength of the vertical velocity spectra). For $z/L_{mw} = 0.16$, $L_{iw} = z$. Kaimal et al. (1972) reported z/L_{mw} to be approximately 0.17 for the Kansas data and Eversole (1979) reported 0.13 for data obtained from the Boulder tower.

The St. Louis turbulence data support the use of L_{iw} as a surrogate for the mixing length. The analysis of these data leading to this conclusion is discussed here.

3. ST. LOUIS TURBULENCE DATA

3.1 Description of Sites

Site 105 was located in a high density commercial area 3 km south of the center of the city and 1 km west of the Mississippi River. Land in the

vicinity of the site was used for trucking, warehousing, and commercial operations. Approximately 25% of the area was covered with predominately two-story buildings (approximately 5.5 m high) of large horizontal extent. Approximately 60% of the area was paved; the remainder was primarily lawn with a few small trees along the streets. The elevation of the site was about 131 m MSL (about 9 m above the elevation of the adjacent Mississippi River). The terrain was relatively flat to the northeast through south, but rose to 178 m within 4 km to the southwest through north. The roughness length, z_0 , was about 0.7 m and the displacement length, d , was 2 m.

Site 107 was located in the northwest section of St. Louis and 6 km from the center of the city. Land for several kilometers surrounding the site was used mostly for older single family and duplex two-story dwellings. Population density was high and the area was considered urban in nature. In contrast to site 105, about 60% of the land area at site 107 was covered by trees (about 12 m high) and grass. The buildings were about 7.5 high and covered about 25% of the area. Paved areas covered the remaining 15% of the land. The site was located on a north-south ridge at an elevation of 158 m MSL. z_0 was about 1.4 m and d was estimated at 6m.

Site 109 was located in a rural agricultural area about 10 km east of the city. In general, farmland surrounded the site. A group of farm buildings was located in the immediate vicinity of the northeast quadrant; small trees and underbrush were located in the immediate vicinity in the southwest quadrant. Small fields separated by hedgerows and scattered homes were located at greater distances in the easterly quadrants. The site was located in the American Bottoms flood plain (elevation about 128 m MSL) approximately 5 km to the west of a 67 m bluff. z_0 for this site was about 0.4 m and d was zero.

3.2 Velocity Spectra and Determination of $L_i(w)$

The vertical velocity spectra (and the horizontal spectra for neutral to stable conditions) may be expressed in the following form:

$$nS(n) = \frac{An}{1+Bn^{5/3}} \quad (3)$$

(Kaimal et al., 1972) where B is related to the spectral peak, A is the value of $S(n)$ as $n \rightarrow 0$, and A/B defines the magnitude of $nS(n)$ in the inertial subrange as a function of n . Eq. 1 reduces to $nS(n) = (A/B)n^{-1/3}$ for large n (i.e., in the inertial subrange, and to $S(n) = A$ for $n \rightarrow 0$).

Eq. 3 was fit to the raw spectral estimates to derive values for A and B from each 1-h time series by a least squares fit over 1 to 1800 and 4 to 1800 spectral points (half of the spectral points for a 1 hour data sample). The latter range, which represents a high pass filtered set of data, was used to fit the w spectra and inertial subrange properties, i.e., the dissipation rate of turbulent kinetic energy (TKE), of the u and v spectra; the former range was used to determine other properties of the u and v spectra, e.g., the peak wavelength and total variance. Further discussion is given in Clarke et al (1982).

Normalized vertical velocity spectra $nS_w(n)/u^2 \phi_e^{2/3} (\phi_e = kze/u^3)$ plotted against reduced frequency, $f = nz/u$, (n is frequency in cycle/s) are shown in Fig. 1 for the following three stability classes for Sites 105, 107 and 109:

stable ($0.5 < z'/L < 1$) ($z' = z - d$), neutral ($0.05 < z'/L < 0.5$), and unstable ($-0.5 < z'/L < -2.0$). All computed vertical velocity spectra were coincident in the inertial subrange (because of the normalization procedure) with the scatter increasing toward the low frequency end. The scatter is no larger than expected from the uncertainty of the individual spectral estimates. The spectral peaks for the St. Louis data for neutral to stable conditions appear to be shifted slightly towards lower frequencies relative to the results of the Kansas study. In general, the St. Louis spectra are in agreement with the Monin-Obukhov (1954) similarity prediction i.e., they appear to be a function of z'/L and the reduced frequency.

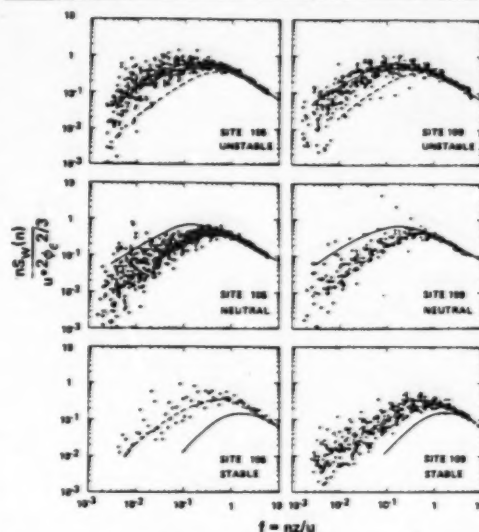


Figure 1. Normalized vertical velocity power spectra for sites and stability classes indicated. Dashed lines represent a composite spectrum for neutral stability derived from the Kansas data; the solid lines above or below represent composite Kansas spectra for $z'/L = -2$ or $+1$, respectively, (Kaimal et al., 1972).

The frequency n_m , corresponding to the energy peak in the logarithmic power spectrum, is obtained by differentiation of Eq. 3, which leads to:

$$n_m = 1.2758^{-3/5} \quad (4)$$

The peak wavelength, L_m , is equivalent to U/n_m . The variance of the time series is given by the integral over the spectrum, with the following result:

$$\sigma_w^2 = 1.98AB^{-2/5} \quad (5)$$

The integral length scale, L_i , can be obtained from the following equation (Buitjes, 1975):

$$L_i = \frac{S(n)U}{4\sigma^2} \quad (n \rightarrow 0). \quad (6)$$

From Eqs. 3, 4, 5 and 6, it can be shown that

$$L_{iw} = L_{mw}/6.21 = U/7.928^{-3/5} \quad (7)$$

L_{iw} was calculated by this method for each 1-hour time series.

4. RESULTS

The hypothesis that $L_{iw} = 1$ can be tested against the form of the nondimensionalized wind profile (Eq. 1) stated as $\phi_m = kz'/L_{iw}$. Plots of kz'/L_{iw} for sites 105, 107, and 109 versus z'/L are shown in Fig. 2. The upper line represents the Businger et al. (1971) form for $\phi_m = kz'/\lambda = (1 - 15z/L)^{-1/4}$ for unstable stratification and $\phi_m = kz'/\lambda = 1 + 4.7z/L$ for stable stratification. The lower line represents the Carl et al. (1973) form, $\phi_m = (1 - 15z/L)^{-1/5}$, for unstable stratification. The plots for sites 105 and 109 are in good agreement with the Carl et al. form for slightly unstable conditions and with Businger et al. for conditions approaching free convection. The neutral value of the ratio at both sites is approximately unity.

The plots of kz'/L_{iw} for site 107 in Fig. 2 are not in agreement with the empirical curves,

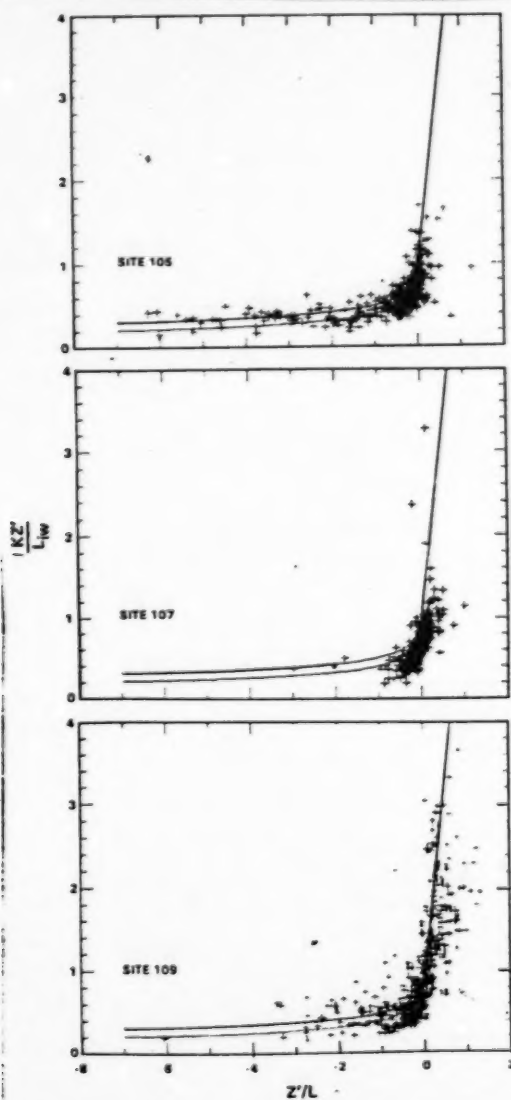


Figure 2. Plots of kz'/L_{iw} vs. z'/L for stations indicated. (See text for explanation of lines.)

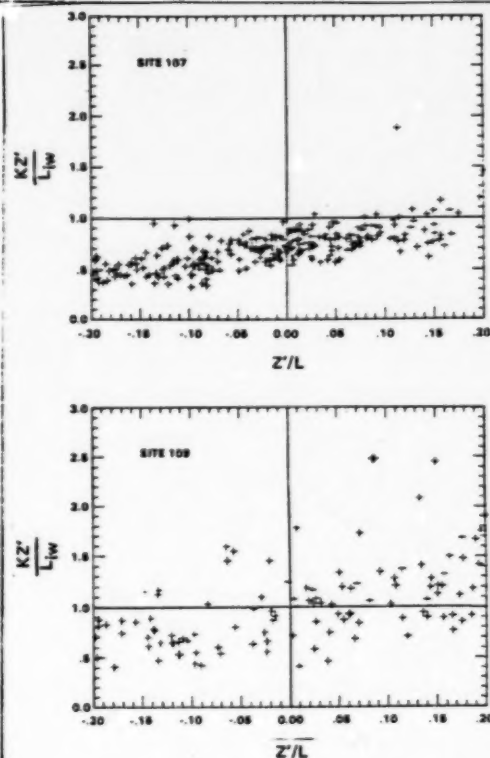


Figure 3. Plots of kz'/L_{iw} vs. z'/L in vicinity of neutral stratification for Sites 109 and 107.

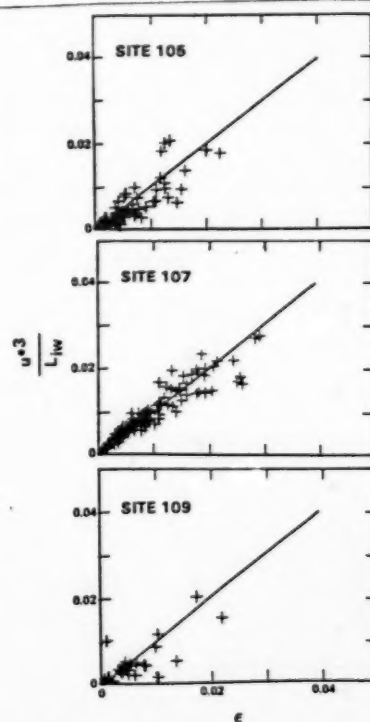


Figure 4. Dissipation of TKE vs. the mechanical production for neutral conditions.

being lower in magnitude over the range of the plots. This is shown more clearly in Fig. 3 where the z'/L scale is expanded in the vicinity of neutral stratification for sites 107 and 109. The ratio for site 107 is about 0.8 whereas the ratio for site 109 is nearly 1.0. We believe the lower ratio for site 107 is real and results from the relative nearness of the measurements to the roughness elements (z'/z_0 is approximately 20 for that site). In the immediate vicinity of the roughness elements, the relevant length scale should reflect the height of the roughness in addition to the height above the surface. We believe that this is the same effect as seen by Garratt (1978). His value of ϕ_m did not converge on 1.0 at neutral stratification for profiles close to the roughness elements (trees). Our situation is similar and the data suggest $\phi_m = 0.8$ for site 107. This result for site 107 does not affect our premise that the mixing length can be approximated by L_{iw} since the modulation of the turbulence arising from surface features and atmospheric stratification are all reflected in this length scale.

The relationship between λ and L_{iw} was used to estimate the shear production term in the TKE equation.* Figure 4 shows a comparison of shear production term derived as u^3/L_{iw} versus the dissipation term (derived from the spectra; see Clarke et al., 1982) for neutral stratification. On average, u^3/L_{iw} is in balance with the dissipation term, further supporting the hypothesis that $L_{iw} = \lambda$.

5. CONCLUSION

The integral scale length of the vertical velocity spectra appears to be an appropriate surrogate for the mixing length. Plots of the ratio kz/L_{iw} for the St. Louis data show a good correspondence to the ϕ_m function proposed by Businger et al. (1971) and Carl et al. (1973). Similarly, by using this approach the shear production term of TKE can be estimated from measurement data at a single level.

* A paper describing the analysis has been submitted for publication in an AMS monograph on nonstationary and nonhomogeneous urban boundary layers.

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